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Soil Compaction Assessment Using Spectral Analysis of Surface Waves (SASW)

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Abstract. Compaction is a process of soil densification in earthworks via by pressing the soil particles with air being expelled from the soil mass, thereby increasing its unit weight. Thus, it is important to evaluate the quality of soil compaction as prescribed in the technical requirement. SASW method is widely used for estimating material properties in layered structures based on the dispersion characteristics of Rayleigh Waves. The small scale at dimension area of 1.0 m width x 1.0 m length x 0.9 m depth was excavated and back filled with laterite soil. The soil was compacted for every layer at 0.3 m thickness. Each layer of soil compaction was conducted compaction test using core cutter methods and SASW test to determine the density and shear wave velocity. The phase velocity for layer 1 was between 112 m/s and 114 m/s, layer 2 was between 67 m/s and 74 m/s and layer 3 was between 74 m/s and 97 m/s. The result shows that the compacted soil layers are not fulfilled the quality of compacted soil layers where supposedly the expected shear wave velocity for the compacted layers should be higher than 180 m/s which is classified as stiff soil.

1. Introduction

Compaction is a process of soil densification in earthworks via by pressing the soil particles with air being expelled from the soil mass, thereby increasing its unit weight. Thus, it is important to evaluate the quality of soil compaction as prescribed in the technical requirement [1]. Conventionally, to assess the quality of compaction, several tests are often performed such as core cutter test, sand replacement cone test and nuclear density test. However, these tests are intrusive and localized thus making it quite time consuming and costly to cover large areas. Therefore, non-destructive test such as spectral analysis of surface wave (SASW) is gaining popularity nowadays to assess the quality of the compaction. The SASW method is an in situ non-destructive testing technique for the evaluation of the dynamic modulus and thickness of layered media [2]. Non-destructive testing used the propagation behaviour of different types of waves in the evaluation of the internal structure of materials. According to Addo and Robertson [3] this method is based on the dispersive nature of Rayleigh wave in order to obtain the shear wave velocity profile for the determination of the material dynamic properties. To obtain a reliable information on the ground, the study of empirical correlation between density and shear wave velocity using the SASW method was conducted.

2. Spectral Analysis of Surface Wave

The spectral analysis of surface waves (SASW) has attracted the attention of researchers because it is a fast, cheap, non-destructive test and an easy to operate [4]. In civil engineering applications, SASW method is widely used for estimating material properties in layered structures based on the dispersion characteristics of Rayleigh Waves [5]. Thus, there is some of the study that has applied using SASW method such as in prediction settlement, quality assessment and determination of flexible pavement and rigid pavement profiles [6,7,8]. The Rayleigh waves are generated into the ground by vertical impact such as hammering, detected by two receivers and recorded by a spectrum analyzer in the SASW method. In addition, for sampling shallow layer, short receiver spacing with high frequency receivers and high frequency sources was utilized. For sampling deeper layer, low frequency receivers were used with long receiver spacing and low frequency sources.

The receivers or vibration transducers produce signals that are digitized and recorded by spectrum analyzer, and each recorded time signal is transformed to the frequency domain using a Fast Fourier Transform algorithm. The phase difference ($\phi(f)$) between two signals is then determined for each frequency, and the travel time ($t(f)$) between receivers is obtained for each frequency as follows:

$$t(f) = \phi(f) / 2phi(f) \tag{1}$$

Where, ϕ (f) is a phase difference for a given frequency in radians and f is the frequency in cycles per seconds (Hz). The velocity of Rayleigh waves is determined as:

$$Vr = d/t(f) \tag{2}$$

Where, Vr is phase velocity and d is the distance between receivers.

The calculations of Vr and wavelength, λr are performed for each applied frequency, and the results plotted in the form of a dispersion curve. Using a simple conversion of wavelength equal to three time depth, the shear wave velocity profile is determined.

3. Methodology

The study was conducted at recess (UTHM), where the small scale represents an embankment fill at a dimension area of 1.0 m width x 1.0 m length x 0.9 m depth was excavated as shown in **Figure 1**. The area was filled with laterite soil and compacted for every layer at 0.3 m thickness. Each layer of soil compaction was conducted compaction test using core cutter methods and SASW test to determine the density and shear wave velocity. Two piezoelectric accelerometer sensors with a sampling frequency range up to 10000 Hz are used to capture the signal generates from an impulsive source. The source generates from the 0.57 kg steel hammer as shown in **Figure 2**. The distance between transient source to the first receiver and distance each receiver is equivalent where the arrangement spacing was set up at 0.2 m. The data for this study was analysed using MatlabR2008a software. The minimum and maximum of the frequency range is selected based from the highest peak of the graph. Then 20% of the value of the highest peak are cut off to select the range of minimum and maximum reliable frequencies. Moreover, the spacing between receiver was also influenced the reliable frequency and wavelength due to the factor of near and far field effect, and thus influenced the target depth. The reliable wavelength range for receiver spacing 0.2 m between 0.1 m and 0.6 m.

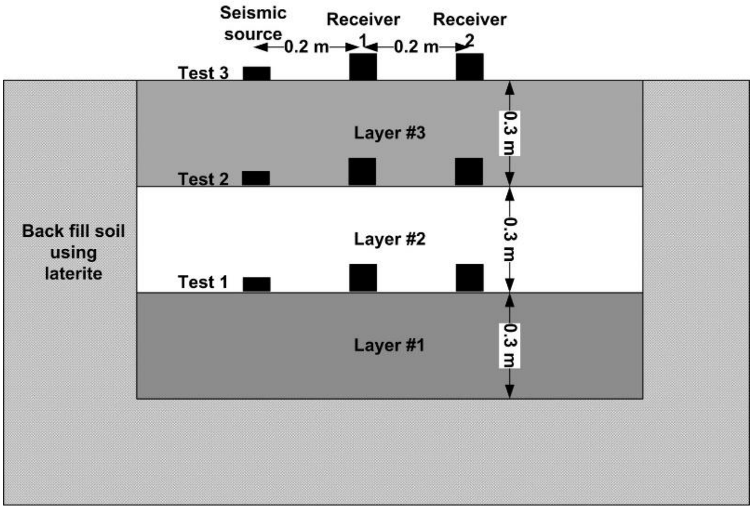

Figure 1. Illustrations of dimension, arrangement of equipment and the stages of testing.

Figure 2. SASW testing on first compacted layer.

4. Results and Discussion

The results of compaction and SASW obtained with receiver spacing 0.2 m for all soils layered is tabulated in **Table 1**. Based the frequency and phase velocity, the wavelengths are calculated based on the phase velocity divided by frequency. Using a simple conversion of wavelength equal to three time depth, the depth was determined. The phase velocity for layer 1 was between 112 m/s and 114 m/s, layer 2 was between 67 m/s and 74 m/s and layer 3 was between 74 m/s and 97 m/s. As suggested by Matthews et al. [9], shear wave velocity, Vs is approximately 1.1 times phase velocity, Vr. The shear wave profile of each tested layer is presented in **Figure 3**. It showed that the velocity obtained were also measured the velocity beyond the tested layer.

Table 1. The results of compaction and SASW tests for each compacted layer.

Layer no.	Dry density, Mg/m3	Frequency, Hz	Phase velocity, m/s	Shear wave velocity, m/s	Wavelength, m	Depth, m
1	1.35	125	102	112	0.82	0.27
		155	114	125	0.74	0.25
		185	111	122	0.60	0.20
2	1.30	60	67	74	1.12	0.37
		74	74	81	1.00	0.33
		88	69	76	0.78	0.26
3	1.33	78	75	83	0.96	0.32
		98	97	107	0.99	0.33
		118	74	81	0.63	0.21

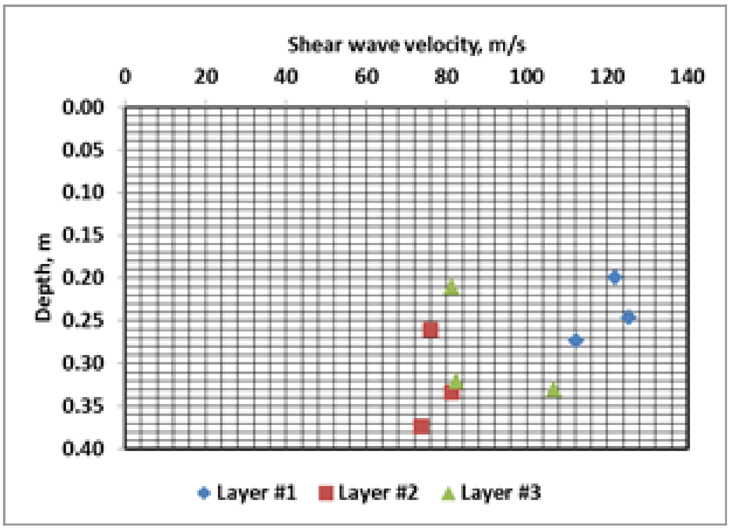

Figure 3. The shear wave velocity profile of each tested layer.

5. Conclusion

The result shows that the compacted soil layers are not fulfilled the quality of compacted soil layers where supposedly the expected shear wave velocity for the compacted layers should be higher than 180 m/s which is classified as stiff soil. The suggested reliable wavelength between 0.1 m and 0.6 m, however the majority of the wavelength results is not fulfilled due to the near and far field effect criterion. Besides that, the result that fulfil the criterion was also lower than 180 m/s. To overcome this problem, the study should use a small hammer to generate the seismic wave, thus able to produce high frequency seismic wave which propagates at shallow layer.

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